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Study on Electrical Discharge Machining I

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ABSTRACT

We studied the working fluid which can increase the erosion rate in condenser discharge machining, and obtained new fluids which are superior ones. In the course of this study, we found the remarkable effect of conductive powder mixed in the fluid, and by applying this fluid we got such high-speed erosion as 80 g/min with only 8 kW power input.

CONTENTS

1. Introduction

In order to speed up the erosion rate of condenser-discharge type electrical discharge machining (E. D. M.), the most effective is to increase energy of single discharge, energy-efficiency and discharge frequency.

When the condenser-capacity and discharge-voltage is risen, discharge energy increases but de-ionization between electrodes becomes difficult and contiuous-arc occurs easily. So, discharge frequency must be smaller than small energy discharge, then there is the limit in erosion rate.

Energy efficiency is defined by the ratio of eroded weight and energy used, and there is the best discharge time according to the energy. This will be described in next report. This experiment was carried out to find working fluid which permits the higher repetition frequency with constant capacity and voltage, that is of good de-ionization characteristic.

In Fig. 1, curve 1 indicates the recovery of insulation between electrode (de-ionization curve), 2, 3 and 4 are ascending curves of voltage (charging

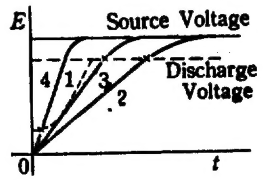

Fig. 1.

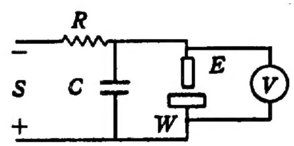

Fig. 2.

curves) with the circuit in Fig. 2, and 0 is the end of electrical discharge. At the point of intersection of two curves next discharge occurs. In high charging rate (curve 4) discharge occurs in such low voltage as 20 V and continuous-arc tends to start. Then with constant condenser and by decreasing charging resistance R, critical resistance value R_0 to continuous-arc is decidable, and with this value de-ionization characteristics can be compared.

2. Critical resistance value

Critical resistance value R_0 depends on flow of working fluid and electrical circuit of impuls-generator. We selected the RC-circuit (Fig. 2) for the convenience of comparison. Voltage ascending of this circuit is straight, and continuous-arc is apt to occur. Blow-out from electrode or agitation of working fluid was not made. p4

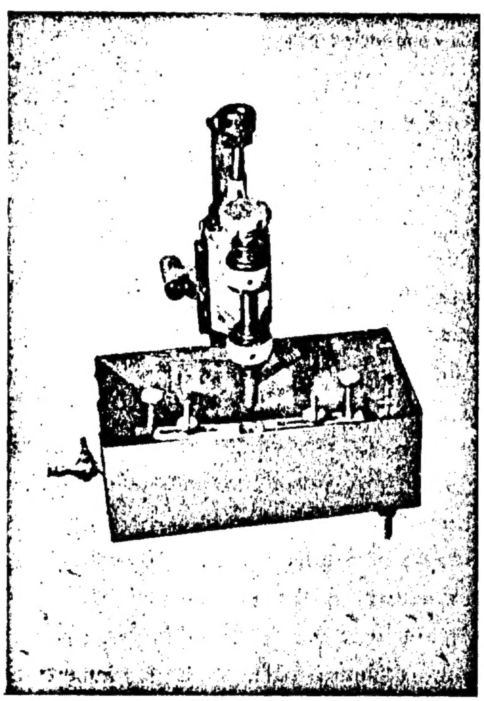

Fig. 3.

A. Experimental apparatus

Experimental apparatus is seen in Fig. 3. Electrical circuit is as shown in Fig. 2, and electrical source S is a DC rotary-generator of 110 V and several 100 A. Charging resistance R is of a solenoid type, condenser C is 6 μF of M. P. type, and leading wire between the condenser and electrode is flexible wire of 40×4 mm sectional area. Working electrode is 1.5 mm ϕ brass wire and workpiece is of 1.3% C-steel.

Electrode is diriven manually with 0.5 mm precision lead screw, and the valtage between electrods is maintained at 45% of no load voltage, that is

50 V. By decreasing the resistance in the course of electrical discharge machining, the minimum resistance which makes 45% regulation possible is decided and that supposed to be the critical resistance value R_0.

In the case of changing working fluid, working tank is washed with benzin several times and dried throughly.

B. Experimental results

Table 1. Critical resistance value R_0

working fluid		R_0 Ω
tap water	H_2O	60
trichloroethylene	$C_2H_3Cl_3$	110
dichloromethane	CH_2Cl_2	120
xylene	$C_5H_4(CH_3)_2$	140
toluene	$C_6H_5CH_3$	180
heptane	C_7H_{16}	190
carbon-bisulfide	CS_2	240
chloro-benzene	C_6H_5Cl	250
kerosene		380
cyclohexane	C_6H_{12}	460
trichloromethane	$CHCl_3$	610
ethyl alcohol	C_2H_5OH	640
dichloroethane	$C_2H_4Cl_2$	720
methyl alcohol	CH_3OH	760
bean oil		840
whale oil		840
transformer oil		920
benzin		950
carbon tetrachloride	CCl_4	950
chinese wood oil		960
machine oil		970
paraffin oil		980
silicon oil		1000
turpentine oil		1010
linseed oil		1050
peanut oil		1150
rape oil		1170
Elox oil		1280
benzene	C_6H_6	1280
substitute Elox oil		1380
acetone	CH_3COCH_3	1515
machine oil SAE30		1560
pump oil		2030
castor oil		2180
ethyl acetate	$CH_3COOC_2H_5$	2600
ethyl ether	$(C_2H_5)_2O$	4800

Critical resistance values of 36 sorts of fluid used for experiment are shown in Table 1, and that disperse widely from 60 Ω to 4800 Ω. There are some fluids superior to kerosene which has been used most widely.

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C. Mixed fluids

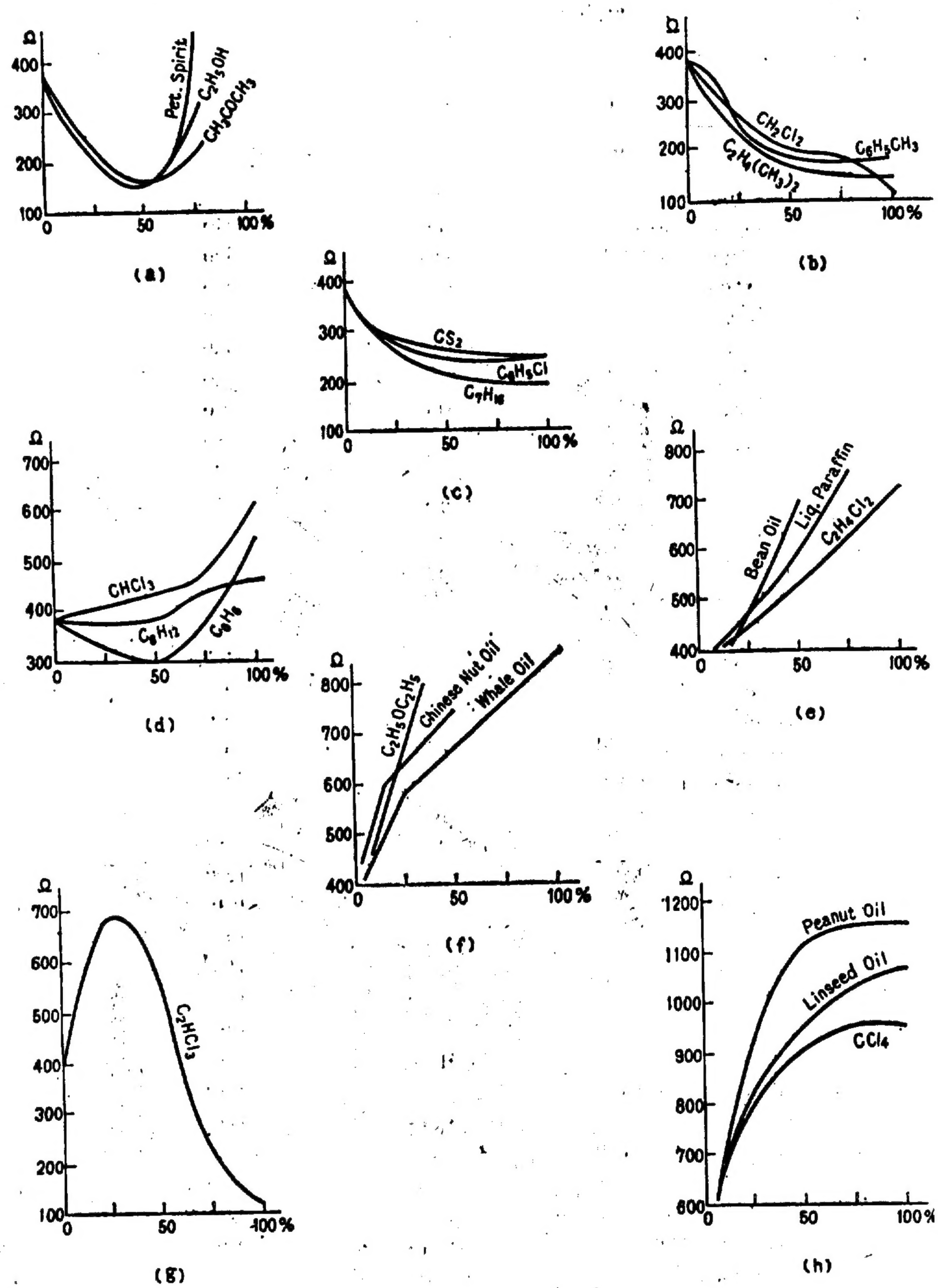

Fig. 4.

Above-mentioned 8 fluids which have lower critical resistance value than kerosene are expensive, and volatile, and ignitable, and they are not suitable for practical use. Therefore, we mixed them with kerosene to improve the property.

Some of them are very effective as shown in Fig. 4. Table 2 shows the

Table 2. Change of mixed fluids

Adition	R_0 (before) Ω	R_0 (after) Ω	Vapourization %
ethyl alcohol	155	280	20
aceton	155	390	49
xylene	160	170	5
toluene	190	210	11
methylene chloride	200	390	36
heptane	210	240	23
carbon bisulfide	260	340	39
benzene	300	280	26

Table 3. Erosion rate

working fluid	R_0 Ω	Erosion rate mg/min
dichlor-ethan	640	4
kerosene	380	10
chlorobenzene	250	14
kerosene 1 vol benzene 1 vol	240	16
kerosene 1 vol toluene 1 vol	210	17
kerosene 1 vol heptane 1 vol	190	17.5
kerosene 1 vol xylene 1 vol	150	19.5

evaporation and change of critical resistance value before and after 66 hours of one to one mixing with kerosene. From the results, kerosene with xylene or toluene is effective.

We tested the relation between critical resistance value and erosion rate, and the result (Table 3, Fig. 5) shows that there is a close connection between them. The comparison of critical resistance value can be a good measure of the erosion rate, and this method is very convenient for searching of working fluids.

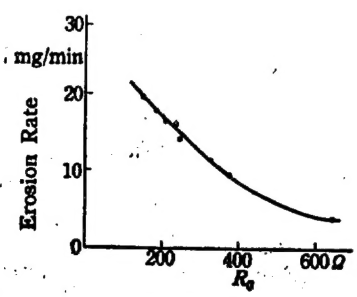

Fig. 5.

The critical resistane value depends upon

condenser capacity and decreases hyperbolically as the capacity increases as the capacity increases as shown in Table 4.

Table 4. Influence of condenser capacity

condenser capacity μF	R_0 Ω
0.011	12,800
0.104	5,400
1	2,030
6	320
10	108
49	19
100	10

3. Fluid with conducting powder

A. Change of property of working fluid

In the above mentioned experiments, working fluids are renewed by fresh fluid after a single usage. In ordinary electrical discharge machining, working fluid is used for a long time, so the property of fluid may change. 07

We machined mild steel workpiece in kerosene with above mentioned apparatus and 9 mm ϕ brass electrode in order to wear out the fluid. Condenser for machining is of of 10 μF and for measuring the erosion rate is of 0.01 μF. The results (Fig. 6) show that in the early period (a-b) erosion rate increases some degree but after that (b-c) decreases. In this experimet we used 100 cc of kerosene, but in the practical machining 50 litre or more kerosene is used, then the maximum erosion rate will occurs after 250 g machining. Assuming the mean erosion rate is 0.2 g/min, this point (b) corresponds to 1200 hours or 150 days. In the mean time, there must be considerable evaporation and carrying-out of working fluid by workpiece, and new fluid is added. Then in ordinary machining condition the state of fluid must be in (a-b). So in general, working fluid increases erosion rate as working time goes on.

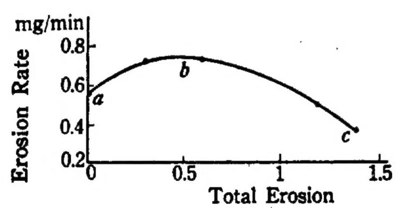

Fig. 6.

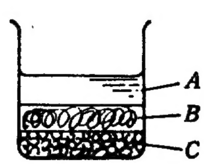

Fig. 7.

Working fluid corresponding to point c (total erosion 1.4 g) was separated in layers (Fig. 7) after 45 hours of precipitation. Layer A is 30 cc of yellowish

transparent liquid, layer B is 30 cc of black misty liquid, and C is 10 cc (0.9 g) of precipitate. As fresh fluid before machining was 100 cc of colorless transparent liquid, 30 cc of them was scattered, evaporated in machining or carried out by workpiece.

The fluid was compared with fresh kerosene. Redwood viscometer measured flow down time of 20 cc of liquid A at 23.5°C as 23.7 sec and that of fresh kerosene as 24.2 sec. Weight of liquid A is 5 mg lighter than fresh kerosene. So there is no significant difference between them.

In liquid B, 0.5 g of chip must be contained. In 100 x microscopic field very small particles are seen and they are misty. This differes evidently from precipitation C which is composed of large particles and not viscous.

Table 5. Used working fluid

Working fluid		Erosion rate mg/min
fresh kerosene		0.56
liquid A		0.51
liqnid B		unstable
liquid B fresh kerosene	30 cc 30 cc	0.3
fresh kerosene precipitation C	30 cc 0.45 g	0.73
fresh kerosene precipitation C	30 cc 0.9 g	1.14
fresh kerosene precipitation C	30 cc 1.6 g	1·19
fresh kerosene graphite powder	100 cc 1 g	1.16

With these, we made the machining tests. The result (Table 5) shows that liquid A does not differ from fresh kerosene, and with liquid B only stable machining without continuous-arc cannot be done, but in the case of mixing it with fresh kerosene it becomes possible, though scarcely. Liquid B resembles to the black material on the electrodes in ordinary machining. It is known widely that black material deposited at the center of electrode machining impossible, but by letting the liquid flow on this point to prevent the deposition the stable machining can be continued.

When precipitation C which has no ability of machining by itself, is mixed with fresh kerosen in the suspended state, erosion rate is higher than kerosene, but such a state does not continue for a long period due to precipitation.

Point (b) in Fig. 6 may be indicate this state. To make sure the fact we mixed graphite powder in fresh kerosene and obtained same result.

B. Working fluid with conducting powder P12

We tried the electrical discharge machining with conducting powder

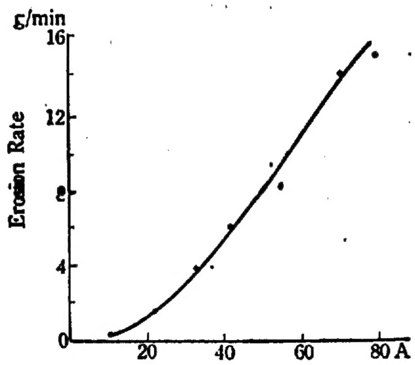

Fig. 10.

By 40 A with electrode of 2 mm ϕ inner diameter and outer diameter of 8 to 18 mm ϕ, erosion rate decreases linearly as electrode area increases as in Fig. 11. In ordinary electrical discharge maching, the result is just the opposit because erosion rate increases as the electrode area increases. This may be related to the mean flow rate on the work surface.

Using 2.5 mm wall thickness of electrode and inner diameter from 2 to 11 mm ϕ, the experiment was made on the influence of flow rate to erosion. The term "gap flow rate" is defined as fluid volume passed on 1 mm of mean circle of tube electrode per min. From this we can appreciate the movement of arc-point and removal of chips.

Table 8. Gap flow rate

inner diameter	mm ϕ	2	3	4	5	7	11
outer diameter	mm ϕ	7.1	8	8	10	12	15
negative pressure	cm Hg	−60	−50	−48.	−53	−45	−46
erosion rate	g/min	4.6	5.7	5.9	6.0	5.8	5.0
flow speed	litre/min	0.8	1.5	2.2	2.4	3.0	3.2
gap flow rate	cm^3/mm min	59	87	115	103	101	78

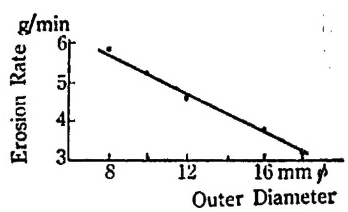

Fig. 11.

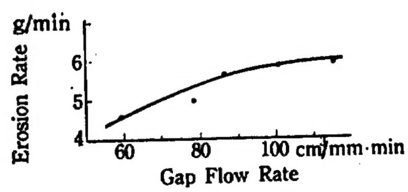

Fig. 12.

From Table 8 and Fig. 12, we can conclude the close relation between the flow rate and erosion rate. When we increase the outer diameter as in Fig. 11, mean diameter becomes larger steeply than inner diameter, and gap flow rate decreases sharply. Then erosion rate also decreases.

We compared the 3 sorts of DC source as to erosion efficiency. The result is shown in Table 9, and 3 phase full-wave rectifier is best among them. Wave form of curreet and drooping character of electrical source seem to have some relation to the results.

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Tacle 9. Comparison of DC sources.

	Working current A	Rotary generator	3 phase rectifier	Single phase rectifier
Erosion rate	40	6.1	7.0	5.4
g/min	67	10.4	12.6	

Table 10. Influence of graphite powder

Electrical Source	Working fluid	Erosion rate g/min
Rotary generator	tap water with erosion chip	0 1.0 4.0 0 5.9 6.0
	tap water with graphite powder 1 g/litre	6.0 5.8 5.8
Single phase rectifier	tap water with erosion chip	5.5 5.0
	tap water with graphite powder 1 g/litre	5.6 5.2

The effect of graphite powder in kerosene is shown Table 10. Discharge is very unstable with tap water only, but by mixing it with eroded chips discharge becomes fairly well and with graphite powder it is very stable.

The influence of graphite powder is shown in Fig. 13, and over 0.3 g/litre the max. result is obtaineined.

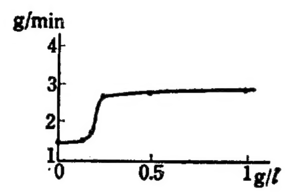

Fig. 13.

The effect of combination of electrode and workpiece materials is shown in Table 11 and 12. Graphite electrode is excellent for 0.4%C steel workpice, and with graphite electrode workpiece with low melting point is easy to erode.

Table 11. Combination of materials

Electrode materials	Sn	Pb	Al	Brass	Cu	M. Steel	Hard metal	graphite
Erosion rate of C-steel g/min	0.0	0.0	0.25	1.0	0.17	0.1	0.1	6.0
Erosion rate of electrode g/min	10.0	37.7	0.5	0.3	0.0	0.0	0.0	0.2

* workpiece material 0.4%C steel

Table 12. Combination of materials

Workpiece materials	Sn	Pb	Zn	Duralmin	Brass	Cu	M. Steel
Erosiod rate of workpiece g/min	‡	‡	20	2.5	2.4	0.1	6.0
Erosion rate of electrode g/min	0	0	0	0	0	0.1	0.2

* Electrode material graphite, ‡ chip clogs tube electrode

B. High speed erosion

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By the Government Invention Bounty in 1958, we constructed an experimental machine (Fig. 14). Electrical source is DC 300 A and pumps for working fluid are the Hypro-pumps with Niron rollers.

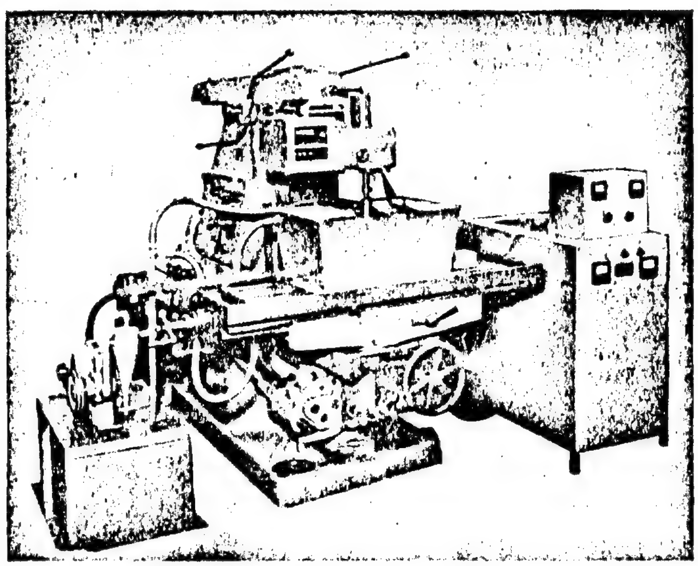

Fig. 14.

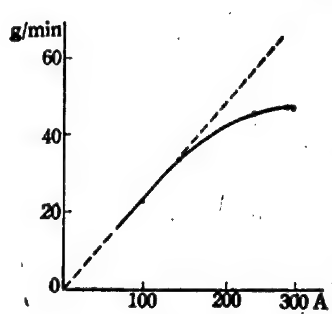

Fig. 15.

The influence of current with 50/30 mm ϕ graphite electrode is shown in Fig. 15. It is fairly good but there is saturation in high current region, it must be due to the slow flow of working fluid.

With 50%-Cu containing graphite electrode erosion rate is 56 g/min, but electrode wear is slightly higher as 8% (weight). With 75%Cu graphite electrode, the result was 30 g/min and

300% respectively, and with soft graphite it was 45 g/min of erosion rate and these are not so good.

We intended to speed up the fluid flow, but our pump had not more ability to suck, so we tried to make the electrode wall thin. Results are shown in Table 13. Thin electrode has good influence, and the erosion rate of 73 g/min **was the highest speed in the world at that time (May 1959).**

Table 13. Thinning of electrode wall

Electrode		Mean current A	Working time min	Working depth mm	Erosion rate g/min
50%-Cu graphite	50/40 mm ϕ	200 300	3 2	18 18	41 62
	50/44 mm ϕ	300	1	12	65
graphite	50/44 mm ϕ	200 300	1.5 1	15 14	50 73

Table 14. Comparison of DC sources

	No load voltage V	Working voltage V	Working current A	Erosion rate g/min	Surface roughness mm H_{max}
Half wave	30	17 16 15	50 100 150	8 12 24	0.5 0.5 1.1
Full-wave	75	33 38 38	50 100 150	8 13 25	0.4 0.4 0.4

The influence of current wave-form was tested by comparing the half-wave with full-wave rectifier. When the mean working current is definite, erosion rate is definite independently of wave form as shown in Table 14. But as the peak current is larger in half-wave than full-wave during discharge period, the removal of metal during discharge is larger, the chip is removed in larger particles and consequently working surface is worse than in full-wave current.

Erosion rate depends on current and not on voltage, so with lower voltage

Table 15. Influence of no load voltage

Working voltage V	Working current g/min	Erosion rate g/min	Surface roughness mm H_{max}
24	50	7	0.4
23	100	14	0.4
19	130	17	0.5

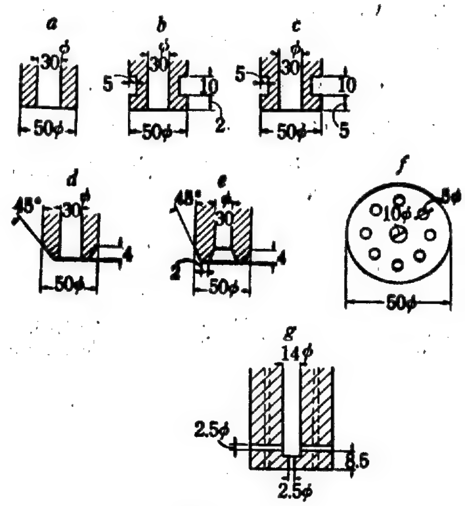

Fig. 16.

source, the input power can be cut down. Then with full-wave rectified and no-load voltage of 32 V, we obtained the expected data (Table 15). As shown in Table 14 and 15, if the current is definite erosion rate is definite, independently of no load or working voltage.

By altering of end form of tube electrode, fluid flow rate and erosion rate will change. The experiment was made with electrode shown in Fig. 16 and with no load voltage of 75 V. The results are shown in Table 16. There was no significant difference between a~e. This must be due to the shallow depth (10~20 mm) of test holes.

Table 16. Influence of end form of electrode

End form	Working voltage V	Working current A	Fluid flow rate litre/min	Erosion rate g/min	Surface roughness mm H_{max}
a	28	150 300	23 21	23 53	0.5
b	28	150	21	23	0.4
c	27 28	150 300	21 21	24 52	0.5
d	27	150 300	20 21	22 54	0.4
e	27 28	150 300	23 22	23 53	0.6

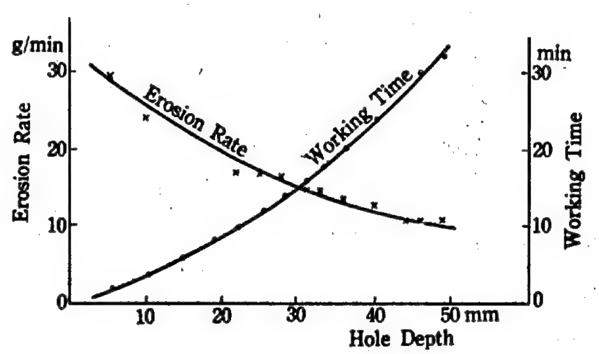

Fig. 17.

The mild steel workpiece was electrical discharge machined with 50/30 mm ϕ graphite electrode in kerosene with 3 g/litre of graphite powder, under the condition of no-load voltage of 75 V, working voltage of 29 V and working current of 150 A. Hole-depth was measured every 2 or 4 min, and the mean drilling speed per 2 min was obtained. Result is shown in Fig. 17. Erosion rate decreases with the increase of depth and erosion rate is only 1/3 of beginning at 50 mm of depth.

This cause is thought to be the lowering of fluid flow, so more powerful sucking will be effective, but the limit of sucking is -76 cm Hg (1 atm.). Therefore lotus-root electrode (Fig. 16f) was used to shorten the distance between the inlet and outlet of working fluid. Blowing-out from the center hole and sucking in surrounding holes were performed (Fig. 18a) or the suction was made from surrounding holes and the fluid was supplied from center hole (Fig. 18b).

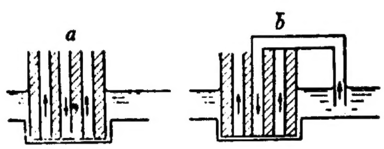

Fig. 18.

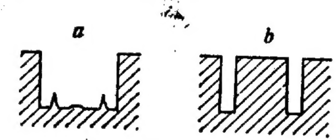

Fig. 19.

Table 17. Lotus-root electrode

	No load voltage V	Working voltage V	Working current A	Erosion rate g/min
blow out (a)	75	27	150	25.0
suck in (b)				25.4

Results are shown in Table 17. Lotus-root electrode is better than straight electrode (Fig. 16a, Table 16a). When deeper hole is machined larger difference will be expected.

Hole machined with lotus-root electrode has slender cores (Fig. 19a) and if things go well there remains hardly no cores, but with ordinary tube electrode (Fig. 19b) how to remove the core is a problem in the case of cavity sinking.

Results of deep hole sinking with lotus-root electrode and suction from the surrounding holes are shown in Fig. 20a. Erosion rate is same as that with ordinary electrode but cores at the bottom is very small. To obtain the small core with ordinary tube electrode, we must use small inner diameter tube, then fluid flow and erosion decreases considerably.

With lotus-electrode 8 holes were drilled radially from center hole to periphery (Fig. 16 g), and workpiece premachined 35.5 mm by electrical discharge, erosion rate decreases only slightly as shown in Fig. 20b.

From the fact that above mentioned, the speed up of fluid flow is most important for high current erosion.

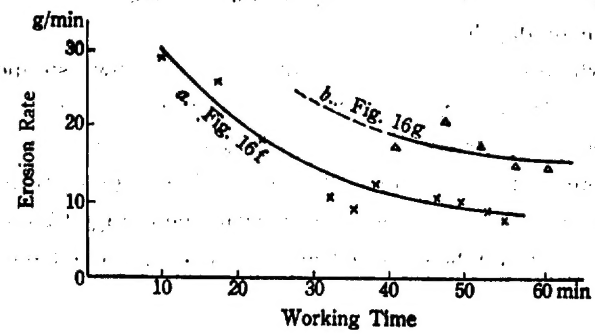

Fig. 20.

Table 18. Erosion rate with pencil electrode

Wave form	No load voltage V	Working voltage V	Working current A	Erosion rate g/min
half-wave	33	17	50	6
		16	100	10
		15	140	15
full-wave	75	38	50	5
		35	100	10

In future in electrical discharge diesinking, pencil-electrode and master pattern will be used. We tested the 10/5 mmϕ tube graphite electrode. Results are shown in Table 18. Wave form of current does not affect erosion rate, but when the current is over 150 A eroded chips clog the tube electrode, and suction comes to be impossible. With larger inner diameter electrode, erosion rate will be higher. In ordinary diesinking machine with end-mill is said that its mean machining rate is about 5 g/min, so the values in Table 18 are fairly good figures.

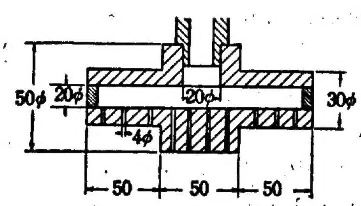

Fig. 21.

Based on above mentioned experiment, we tried to obtaine the best erosion rate with 50/40 mmϕ graphite electrode (like Fig. 16e), using the pump with the max suction power and mild steel workpiece. With no load voltage of 75 V, mean working current of 300 A, erosion rate was 83 g/min, electrode

wear 2% (weight) and surface roughness 0.4 mm respectively.

With graphite electrode as shown in Fig. 21, single phase full-wave rectified current of 100 V no load voltage and tap water with 3 g/litre graphite powder, we machined the 76 cm^3 of mild steel in 22 min by 200 A and 40 min by 100 A.

C. Electrical discharge machining with double circuits

Above mentioned 83 g/min erosion necessitates the 75 V×300 A source, then the source efficiency is 3.7 g/kW which is superior to 0.5 g/kW in ordinary condenser discharge. Source voltage of 75 V is not to maintain electric-arc but to ignite arc, then it must be very effective for source efficiency to use separate electrical source for ignition and for maintaining arc respectively.

Using such circuit (Fig. 22), we obtained 80 g/min by 8 kW source, that is 25 V 300 A and 80 V 5 A. Decreasing the lower source voltage further, we can expect more efficiency. And machining with electrode shown in Fig. 21 will be completed within 13 min.

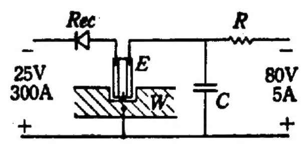

Fig. 22.

D. Erosion mechanism

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Oscillogram of this discharge is showu in Fig. 23a, and represents typical arc discharge. By spliting the electrode (Fig. 24) the current of segment

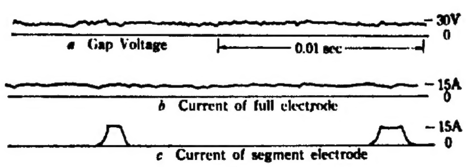

Fig. 23.

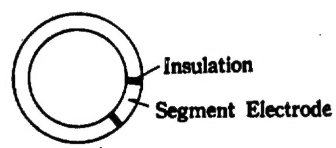

Fig. 24.

electrode (c) as well as of full electrode (b) were recorded. From the fact that current of full electrode is constant but the current of segment electrode is intermittent, we can conclude that arc is running over the electrode surface. This is due to the motion of conducting particles caused by working fluid flow. Then arc is not maintained in one position and heat effect on the worked surface is not very deep (Fig. 25). In the photograph depth of heat treated layer is nearly the same as surface roughness value (0.4 mm).

Fig. 25.

As the flow rate that is running speed of conducting particle is speeded up, foot of arc runs fast and stationary-arc turns into running-arc. In the running-arc, arc column is shrank and temperature rises. Then erosion efficiency is promoted compared to same energy input. Furthermore, with increase of arc running speed, eroded chip becomes smaller and is removed faster. Then, as deposition on the working surface or in the tube electrode is small, larger working current becomes usable.

5. Conclusion

We started this research with the study of working fluid for condenser discharge, trying mixed fluid and fluid with conducting powder, and lastly developed the running-arc process. Running-arc process is efficient and simple, but is not suitable for finish machining bacause the motion of arc is limited and staying period of arc on one point is far longer than condenser discharge period. Practically we must adopt it in combinatiin of the ordinary condenser process for finish machining. END

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